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Chapter 6—Daylighting

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1. On natural light

To talk of architecture is to talk of light, and above all of natural light. It is not just a physical means enabling us to see the exterior and interior material form of buildings; rather, it provides architecture with its main energy component, necessary for the existence of a rich, integrated duality of matter and energy which, beyond mere usefulness, generates an aesthetic sensation in the users.

It is for this reason that great architecture has always been associated with natural lighting, generating it with and within itself. From the categorical eloquence of the single opening of the Pantheon to the magical complexity of the Germanic baroque, via the increasingly finely wrought Gothic cathedrals, natural light has been a deciding factor in the quality of space. In spite of this, the role played by light in architectural aesthetics is often ignored, great works being analysed with parameters that are concerned purely with style and geometric form. In the narrower sense of architectural quality, the aesthetic power of light is what differentiates architecture from mere construction when we visit a building. Such it has been described by the great commentators on architecture, from Vitruvius to Bruno Zeni, when they speak of light with the enthusiasm that art alone can arouse.

Yet when we attempt to analyse the role of light in contemporary architecture, we find a huge vacuum. Today's representative buildings almost totally neglect the important part natural light could play in their interiors. Excessive use is made of artificial systems, and architecture is conceptualized as glass geometry, with paradoxical curtain walls that instead of communicating with the exterior, create impractical barriers. A point is thus reached where the interior environment, which is theoretically controlled, frequently becomes more inhospitable than the exterior. In such cases, architecture works 'worse than the climate'.

Today, it is essential for the architectural profession to recover the systematic use of natural light. To this end, designers should be made aware of how spaces work in conjunction with light, and the best way to do this is not by way of elegant or sophisticated technical solutions. It is sufficient to be acquainted with certain basic principles, which can be divided into two well-defined areas: the physics of light and the physiology of vision. These basic principles can lead to the practice of natural

light in design with greater efficiency than would be the case with the technology of particular solutions and systems.

The physics of light allows us to understand how this electromagnetic radiation behaves in architectural space. By knowing its basic laws and its interaction with the surfaces that reflect, absorb and transmit it, we can control the effect of light on buildings and its distribution in interiors.

The physiology (and psychology) of vision facilitates understanding of human reactions in lit spaces. By knowing the basic principles of perception and comfort, as we design buildings we can control the relationship between light and the users of their exterior and interior environments, and in this way define the lighting aesthetically and functionally from the very start of the project.

Finally, providing a building with natural light is more than just the solution of a problem of energy consumption; more, even, than an aesthetic resource easily incorporated into the architecture. Natural light in architecture must be part of a more general philosophy that reflects a more respectful, sensitive attitude in human beings towards the environment in which they live.

2. Basic physical principles

Various phenomena affect man's environment: radiation, air vibrations, temperature and so on. All these manifestations of energy are to some extent of human senses, although in the case of light the part of the phenomenon which is perceived is very small in comparison with the phenomenon's total field (electromagnetic radiation).

2.1. *The physical principle of electromagnetic radiation*

Electromagnetic radiation is a form of energy transportation by means of periodic variations in the electromagnetic state of space, and can also be interpreted as the movement of immaterial particles (photons).

The wide field of electromagnetic radiation is classified according to its wavelength (λ) or its frequency (f) into a number of zones of what we call the radiant spectrum, which is equivalent to doing so according to its technologically perceptible effects. In this spectrum, visible light occupies an extremely narrow band (Fig. 1).

It is important to bear in mind that the wavelength and the frequency of the propagation of a vibratory movement are related to the speed of propagation (c) thus: $\lambda = c/f$.

Electromagnetic radiation is caused by variations in the atomic structure of bodies, when the orbital situation of the electrons is altered; on returning to their original position they cause photons to be emitted, the excess energy thus being eliminated in the form of radiation.

There are two main types of radiant sources, discharge and thermal sources, although for the purposes of natural light it will suffice to consider the latter.

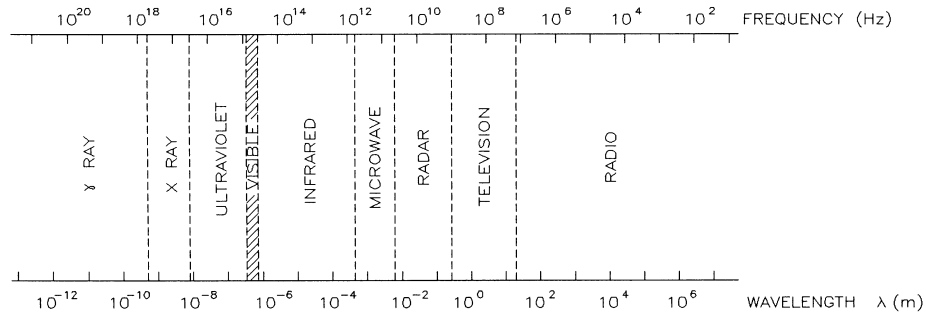


Fig. 1. Radiant spectrum.

Thermal sources emit radiation as a result of the thermal agitation of matter, and display a characteristically continuous spectrum in the field of wavelengths they cover (Fig. 2).

Under normal conditions, thermal sources emit mostly infrared radiation, but as the temperature of the emitter rises, not only does the amount of energy increase but also the maximum value of emission moves towards increasingly shorter wavelengths. In this way, as the radiation temperature increases it moves further into the visible band of the spectrum, until, at a temperature of around 6500 K, the maximum is located in this zone. It is no coincidence that this temperature is approximately that of the surface of the sun; the field of activity of human sight is adapted to the highest values of radiation in its planetary environment (Fig. 3).

2.2. Units and fundamental equations of light as energy

In lighting, four main units are used to describe light and its effects.

Luminous flux measures the amount of light per unit of time, and is abbreviated as Φ . Its unit of measurement is the lumen (lm).

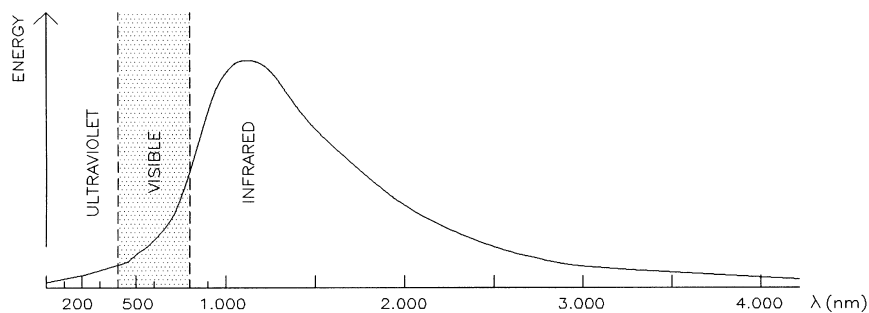


Fig. 2. Energy/wavelength curve for a thermal source.

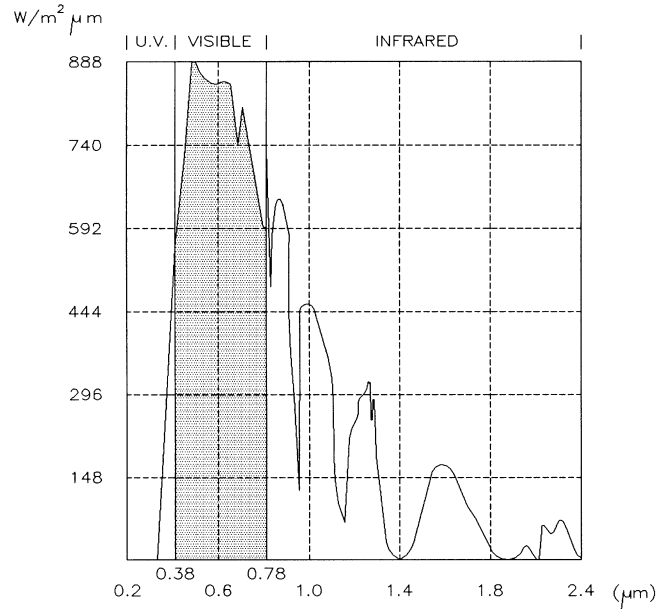


Fig. 3. Spectrum of solar radiation.

Luminous intensity measures flux in a given direction, and is abbreviated as I . Its unit of measurement is the candela ($\text{cd} = \text{lm sr}^{-1}$) (sr: unit of solid angle in which the surface subtended on a sphere is equal to the square of the radius).

Luminance indicates the lightness of an emitting surface for an observer, and is abbreviated as L . Its unit of measurement is the candela m^{-2} (cd m^{-2}).

Finally, illuminance measures the flux reaching a given surface, and is abbreviated as E . Its unit of measurement is the lux ($\text{lx} = \text{lm m}^{-2}$) (Fig. 4)

In any light phenomenon it can be observed that the light originating from an emitting source expands through space, and as it moves away from its source the illuminance that it produces on a surface decreases by the square of the distance. Equally, if the surface is not orthogonal to the incident beam, the illuminance decreases by the cosine of the angle of deviation, resulting in the following:

$$E = (I/d^2) \cdot \cos \alpha \quad (1)$$

In the case of direct solar radiation, given the great distance of the emitting source, variation due to distance is negligible on the Earth's surface and the beams are considered parallel, which means that $E = I \cdot \cos \alpha$.

2.3. The visible spectrum

Light not only transports energy but also has colour, as a result of the distribution of energy over the different wavelengths of the visible spectrum; a specific colour

Φ = flux

I = Intensity

E = Illuminance

L = luminance

r = reflection coefficient

S = illuminated surface

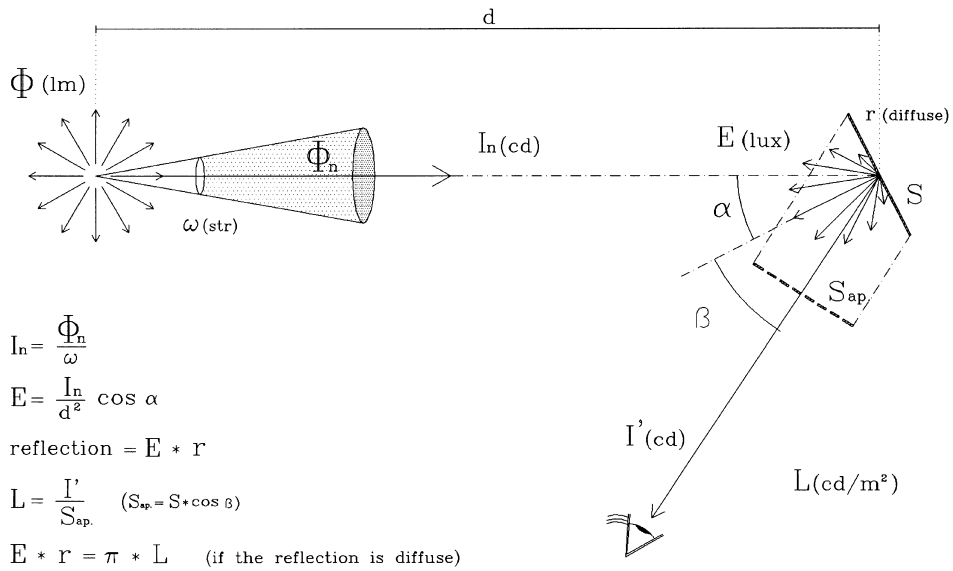


Fig. 4. The four units.

corresponds to each wavelength, as in the colours of the rainbow. Sunlight covers all the zones of the spectrum (Fig. 5).

In the field of lighting technology specific units are used to indicate the chromatic characteristics of light, thus:

The colour temperature (T_c) expresses the colour of a source of light by comparing it

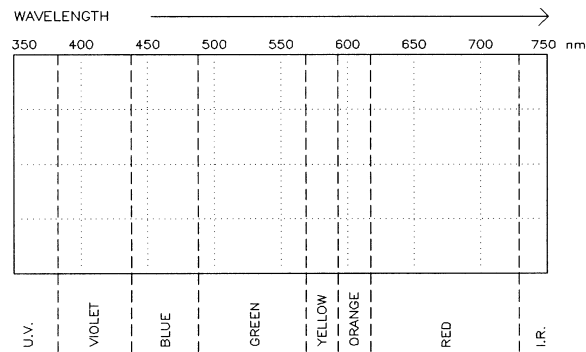


Fig. 5. Spectral colours.

with that of the light issued by a black body at a given absolute temperature, its unit being the kelvin (K). As the black body changes spectrum according to temperature, at around 3000 K the light is reddish, in the region of 5000 K the distribution cancels out, and at higher temperatures it is bluish. T_c is defined as the temperature to which a black body must be heated for the light it emits to be of a similar colour to the light being measured. In the case of natural light we note that its colour temperatures are in the order of 6000–6500 K, in keeping with the real temperatures of the surface that emits this light (the sun's corona).

The colour rendering index expresses the reproductive capacity of light on the colour of the objects that it illuminates. It is abbreviated as R , and is expressed as a percentage. In order to have good chromatic reproduction, light must have energy on all wavelengths, as is the case with sunlight, which is, moreover, the type with which we are most familiar. In practice, the R of natural light is 100%.

2.4. *Light and the limits of space*

Light is propagated through space at a speed that for architectural purposes can be regarded as instant, but on encountering a material obstacle is partly reflected and partly absorbed by the surface (being transformed into heat). Some of the light may also be transmitted to the other side of the obstacle. The coefficients of reflection (r), absorption (a) and transmission (t) give respective ratios for the incident light that is reflected, absorbed and transmitted by a given surface. The sum of the three coefficients will always yield unity: $r + a + t = 1$.

The phenomena of the reflection and transmission of light from surfaces are very important for the understanding of the behavior of light in architectural spaces. As energy can be reflected qualitatively in a different way depending on the type of surface, we shall consider the different possible types from both the spectral and geometric viewpoints.

- (a) from the spectral viewpoint, surfaces can display different behaviour for the different wavelengths within the visible zone. In this way, natural light can take on various colours, on being reflected or transmitted by coloured surfaces. This is the specific reflectance or transmittance (r_1 or t_1), which determines the behaviour of a given surface for light of a given wavelength (with its associated colour). The mean weighted value of r_1 or t_1 for a given radiation (in this case sunlight) will give us the value of the reflection coefficient of the surface. As a rule, the radiation reflected or transmitted by a surface reproduces the spectrum of the incident radiation, modified by the values of the various specific reflections or transmittances (r_1 or t_1) (Figs 6 and 7).
- (b) from the geometric viewpoint, the finish and the internal structure of bodies can affect the geometry of the transmission or reflection. As long as the material irregularities are of a similar order of magnitude to the wavelength of the light, the light will be diffused. If these irregularities are significantly smaller, regular reflection or transmission will occur, with no modification of the geometry of

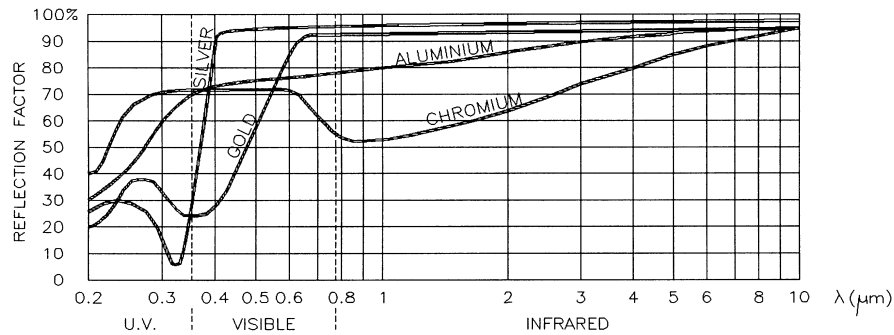


Fig. 6. Spectral reflectances, of different materials.

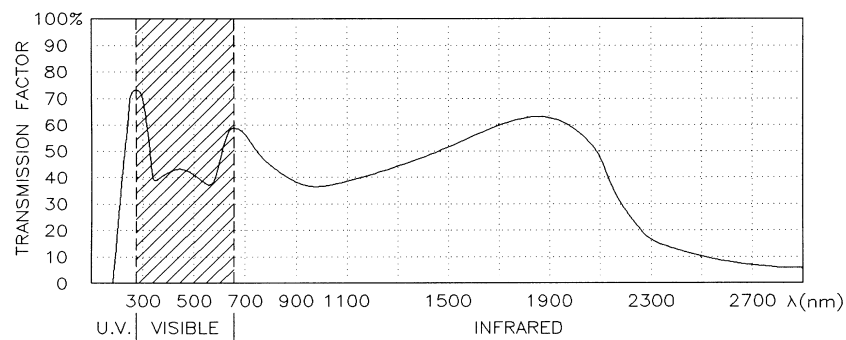


Fig. 7. Spectral transmission through a glass.

the incident light. In practice, three basic types of geometric behaviour can be distinguished (Figs 8 and 9).

As the wavelength of light radiation is very small, most surfaces with which we work in architecture present reflection of a diffuse type, and light does not pass through them. Only highly polished surfaces and those with an ordered internal molecular structure (crystals) display regular behaviour regarding reflection and transmission.

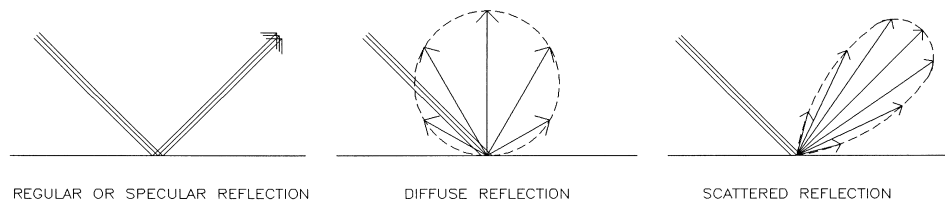


Fig. 8. Reflection—geometric behaviour.

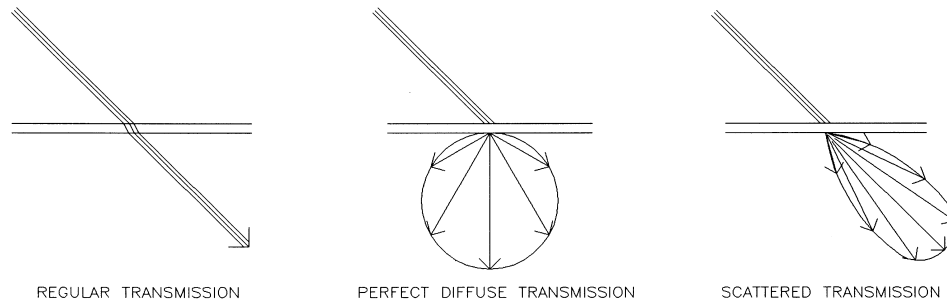


Fig. 9. Transmission—geometric behaviour.

In the case of diffuse reflection or transmission, the resulting distribution of the light is such that the luminance L of the surface, observed from any direction, is constant and has the value:

$$L = (E \cdot r)/\pi \quad \text{or} \quad L = (E \cdot t)/\pi \quad (2)$$

This formula, in combination with the one in Section 2.2. above, makes it possible to assess the behaviour of natural light in architectural spaces (see Section 6).

In architecture, where most surfaces have diffuse reflection, this behaviour tends to distribute natural light more uniformly around interior spaces. Surfaces with regular (or specular) reflection can be useful for reflecting light, especially the direct radiation of the sun, in particular directions which are considered appropriate. Equally, transmitting surfaces are normally regular or transparent, thus allowing the entry of direct sunbeams without varying their geometry and at the same time a view, usually considered a favourable effect. Nevertheless, when it is sought to diffuse light entering an interior, or to avoid the visual discomfort of a patch of direct sunlight, or even to preserve visual privacy, diffusive materials or systems are used which avoid the regular transmission of light to the interior.

2.5. Absorbed light

In both reflection and absorption processes, some light is absorbed by the obstacle and its energy is converted into heat. This disappearance of energy from the world of light can have important technical consequences that are often neglected in the design of buildings.

Direct sunlight has a relatively high energy density, in the region of 1000 W m^{-2} . Because of this, light shining into an interior, especially when it surpasses visual needs, can cause overheating. This effect, which can be positive in winter and at high latitudes, becomes hazardous in hot and temperate climates. For this reason, it is just as important to be able to regulate strong external solar radiation shining in as it is to provide appropriate interior lighting in circumstances of poor natural light.

3. The physiology of vision

Light in general and natural light in particular act upon human beings when perceived by our sense of sight, and this action can be considered to have two main consequences. The first and more general of these is our perception of the world, which is conducted by means of sight and provides our brain with information about our surroundings. This perception is also important aesthetically, and is very important in architecture for both reasons. The second consequence is more specific and consists of the discomfort light can cause our sense of sight, particularly the distribution of luminances in the field of vision, which affects the users' comfort and is therefore also decisive in the design of spaces. As both architectural consequences depend directly on the physiological functioning of sight, we shall begin by studying the human eye.

3.1. *The eye and sight (visual perception)*

The sense of sight is based on the functioning of a highly specialized organ, the eye. This organ features the pupil, which regulates the amount of light entering the eye by means of an opening the surface area of which can be adjusted in a ratio of 1 : 16. The more closed the pupil is, the less energy enters, but the vision is sharper and with a greater depth of field. The crystalline lens changes shape to regulate the focus, maximum deformation occurring with near vision. From the crystalline lens, the light crosses the vitreous humour that fills the eyeball and so strikes the retina, where the images focused by the crystalline lens are formed. This retina is a 'particle', sensitive to the amount of light by means of cells called rods, and to the amount and the colour (wavelength) of the light by means of other cells called cones. In the centre of the retina there is a small concavity called the fovea centralis, containing only small, tightly packed cones, which is the region providing sharp vision (Fig. 10).

This visual system is able to detect both the amount of energy falling on the eye and the spectrum of the light to which it is sensitive. Between certain limits, it also has the capacity to regulate various effects, such as the amount of light that enters or the focussing of the images on the retina.

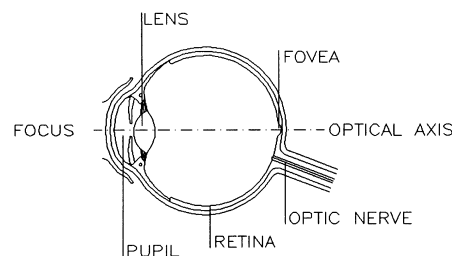


Fig. 10. Structure of the human eye.

From the retina, where the light photons affect the sensory cells and generate nervous impulses, the signals are sent to the brain along the optic nerve and are interpreted as images.

The human eye responds to the amount of energy it receives with sensations that do not correspond linearly to the stimulus. As is also the case with the other human senses, sight follows an approximately logarithmic law according to which equal increases in the stimulus do not imply equal increases in sensation; rather, the latter are smaller when energy levels are high than when they are low. Consequently:

$$S = K \log E + B \quad (3)$$

(where S = sensation, E = stimulus, and B and K = constants)

This type of reaction permits the human senses to take in wider fields of energy levels, but also means that when assessing the effects of light, a given increase has a different value depending on the level of departure. Thus, an increase of 1 m² in a light opening has a huge effect if the previously existing opening measured 1 m², whereas an increase of 1 m² in a space already possessing 10 m² of opening results in very little sensation of increased light in that space.

In addition to this basic sensory mechanism, sight can adapt to different energy levels using other systems. We have already seen how the pupil varies the surface area through which light enters in a ratio of 1 : 16 by means of a retroactive mechanism. In addition to this, the cells of the retina work in various fields; the rods are the only cells that register luminances below 10 cd m⁻², just as only cones respond in conditions above 300 cd m⁻²; between these limits, the two types of cells work together.

The cones allow the perception of colour; sensitivity is greatest in the yellow–green region, gradually fading until it fails completely at the two ends of the spectrum. This vision by means of the cones is called photopic vision. In vision using the rods, known as scotopic vision, colour is not registered, and maximum sensitivity is located in a zone with a short wavelength (blue), the so-called ‘Purkinje effect’ (Fig. 11).

The sensitivity curve of the eye with photopic vision can be used to define the units

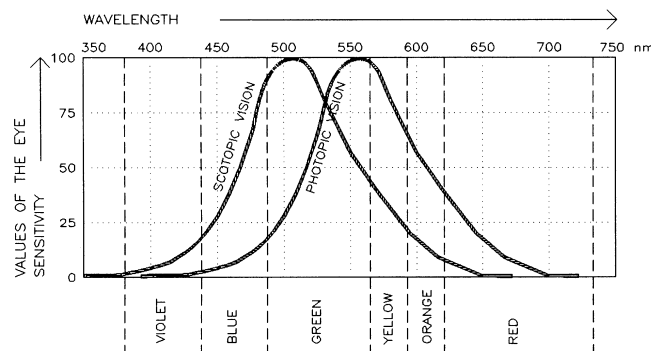


Fig. 11. Sensitivity curves of the human eye.

discussed in Section 2.2. The luminous flux results from affecting the total radiant flux by the sensitivity coefficient of the eye for each wavelength.

$$F_l = F_r \cdot V_{(0)} \cdot 680 \quad (4)$$

(where F_l = luminous flux in lm, F_r = radiant flux in W, and $V_{(0)}$ = sensitivity coefficient)

3.2. Temporal sensitivity of vision

The human senses tend to adapt constantly to stimuli and to be sensitive according to the mean energy values of their perceptual field. In the case of sight we have already discussed the basic mechanisms of adjustment to change: the pupil, the cones and rods and the general sensitization of the retina.

In order to adapt to a change in the conditions of mean luminance of the visual field, the eye needs a period of time which varies according to whether the change is from light to dark or vice versa. More than 30 min is generally considered to be necessary for good adaptation when changing from light to dark conditions, compared to just 30 s or so to adapt from darkness to light. In fact, they should be thought of as adjustment curves of a logarithmic type, with rapid response at the beginning but tapering off as time passes. Perfect adaptation from light to dark is a matter of hours, but the first instants are the most noticeable.

This phenomenon is important in architectural design, especially considering that correct perception depends more on the balance of luminances in the field of vision than on the absolute level, since sight possesses capacity for adaptation in an extremely wide field of energies, with correct rendering from mean luminances as low as 50 up to 25,000 cd m⁻². For this reason, the absolute value of light levels in architectural spaces is often less important than it is for the user to be able to move gradually between different light levels and thus adapt.

3.3. The spatial perception of the human eye

The human eye has an approximately semispherical field of vision (2π steradians), with a narrow, central solid angle of precise vision, corresponding to the location of the cornea in relation to the retina. Towards the edges of the visual field, vision is blurred, the perception of shapes rapidly being lost, while that of movement remains more intact (Fig. 12).

Our eyes are usually in constant movement, switching our precise vision from one area to another of the visual field that is under the global control of the periphery of the retina. The movement of the head complements our capacity for the visual perception of our environment, but there always remains an eclipsed area at our rear which we neither perceive nor control with our sight and which requires the aid of our sense of hearing if we are to feel in control of our surroundings. For this reason, the position of people in relation to the space they occupy can be important, especially in interiors with acoustic difficulties.

Our sense of sight also allows us to pinpoint the direction of the objects that

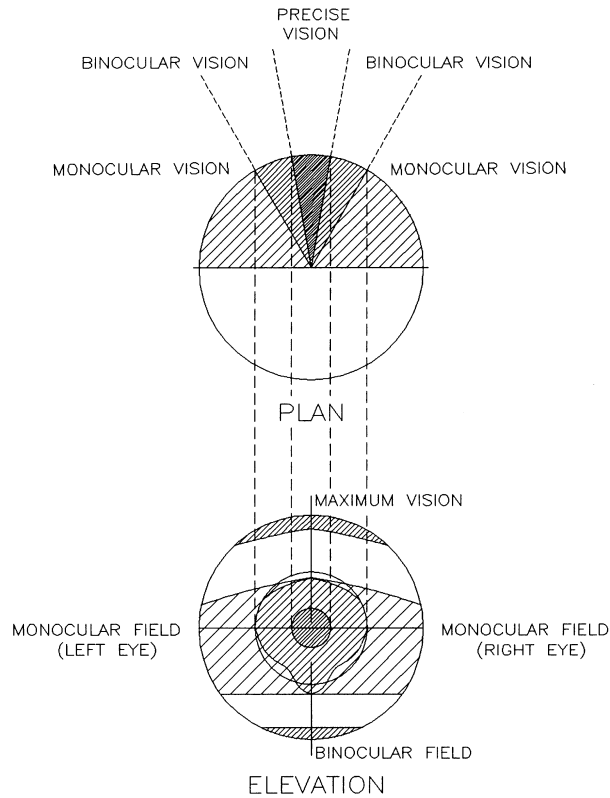


Fig. 12. Plan and evaluation of visual field.

surround us, basically by directing the head and eyes towards that which we are observing. The action of the muscles informs the brain of the direction in relation to our body, to a large extent on the basis of experience.

Judging distance is more complex, and involves a number of mechanisms. Firstly, there is the deformation of the crystalline lens as it focusses the image, which makes it possible to judge very short distances. Furthermore, binocular vision, with the difference between the image that each eye perceives, enables us to recognize the relative location of the objects in our field of vision, while at the same time the convergence of the eyes assists us in judging short distances. Finally, it is the learning process that contributes most to informing us how far away objects are located, as we simply weigh up their apparent size on the basis of previous experience. The only drawback to this is that it is an unreliable system in novel environments or ones with a different scale to normal, an effect which has frequently been used as an architectural device to produce special sensations in the observer.

3.4. *Visual comfort*

When we talk of comfort we mean well-being or lack of discomfort in a given environment. Several different causes may be involved in this concept, since all the senses are receiving stimuli simultaneously, in addition to which, other more difficultly recognizable factors are also present. Nevertheless, comfort is traditionally analysed independently for each of the main senses, including sight.

On the subject of comfort we make a distinction between comfort parameters, assessable values of the energy characteristics of the environment, and factors, which depend on the user and influence the appreciation of the parameters. Comfort depends on the relationship between the two, and although architectural design essentially effects the parameters, the factors of the user (age, type of activity, etc.) must be taken into account in order to ensure that the design fulfils its objective.

Visual comfort depends, as is logical in a basically informative sense, on how easily we can perceive that which interests us. As a result, the primary requirement is that there must be the right amount of light (illuminance) for our visual acuteness to distinguish the details of what we are observing. In accordance with this, the first parameter is illuminance (lx), with recommendable values that vary depending on the circumstances and the glare conditions (which constitute the second parameter to be considered in visual comfort).

Glare, considered as a comfort parameter, is the unpleasant effect caused by an excessive contrast of luminances in the visual field. As a rule, this effect is due to the existence of a small surface of great lightness (luminance) in a field of vision with a considerably lower mean value, normally as a result of a lamp or a window.

Physiologically, we distinguish two types of glare. ‘veil glare’ is that produced by a bright spot on a very dark background, such as a streetlight or a star at night. As the beam of light enters the eye it causes a degree of diffusion in the vitreous humour, which makes us see the point of light as being enveloped in a veil or producing rays in the shape of a cross or a star. The other type, called ‘adaptation glare’, is more important in architectural design, and is caused when the eye adapts to the mean luminance of a visual field where there is a great variation in luminance values, with extremes that are outside the capacity for visual adaptation and are therefore not seen.

Glare can also be classed according to the incidence on the eye of the excessive beam of light. When it strikes the fovea centralis it is called direct glare, or incapacitating glare, since practically nothing is visible. If the incidence is elsewhere on the retina it is called indirect glare; this type can hinder vision without actually preventing it, and is also called disturbing or perturbing glare. It should be borne in mind that in many cases the same terminology (direct/indirect) is used to define and distinguish the glare produced directly by a source of light from that produced by a reflection on a glossy surface (such as a glass-topped table) (Fig. 13).

Glare is a phenomenon which it is difficult to evaluate, although this can be achieved by analysing the various different luminances present in the field of vision. As a first approximation, the following values are recommended as suitable for a work environment: contrasts of 1–3 between the observed object and its immediate back-

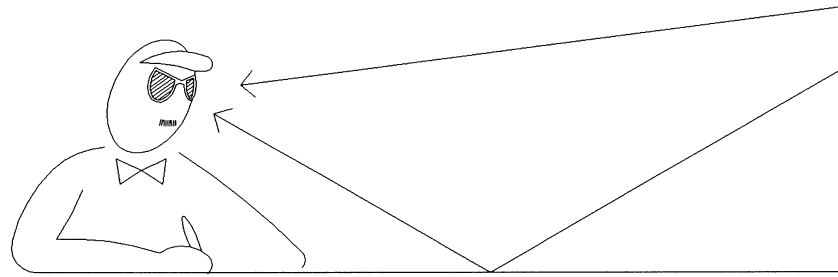


Fig. 13. Direct/indirect glare.

ground, 1–5 between it and the work surface as a whole, and 1–10 between it and other surfaces in the field of vision. In a more accurate analysis, the following concepts are brought into play:

$$g = \frac{L_s^a \omega^b f(\theta)}{L_B} \quad (5)$$

where:

L_s = luminance of the light source

ω = solid angle of the source from the eye

$f(\theta)$ = function of the direction from which the light arrives (value 1 if it arrives perpendicularly to the eye and value 0 if it arrives laterally)

L_B = luminance of the background to the light source

a and b = coefficients with typical values 1.8 and 0.8

The sensation of glare grows as the value of this glare constant g increases. As, subjectively, growth in discomfort due to glare approximately follows the logarithmic law of sensation, the glare index (G) is defined thus:

$$G = 10 \log_{10} g \quad (6)$$

When the value of the index G exceeds 10 the glare is noticeable, from 16 to 22 it is bearable, from 22 to 28 it is uncomfortable, and for higher values, intolerable.

A third parameter for visual comfort is the colour of the light; derived from the concepts of colour temperature and colour rendering index, discussed above, the colour of the light is not only a quality factor as regards perception but an element of comfort or discomfort to be taken into consideration. In connection with this, the Kruithof graph establishes a relationship between the colour temperature of the light and the illuminance, and defines a field of compatibility between the two values.

In the case of natural light, the colour of the light will have little influence on comfort, since its chromatic characteristics are taken as the theoretical ideals. Nevertheless, it should not be forgotten that, as the colour temperature in this case is very high (around 6500 K), in the case of low lighting levels the sensation can be excessively cold, and therefore unpleasant. The reflection or transmission of light to shift its spectrum towards warmer tones can improve the users' visual comfort in such cases.

Considering all the above and always bearing in mind the relative value of these data, we can state typical values for light parameters in relation to the factors of the user (Tables 1–5).

4. Daylighting in architecture

The analysis of light on both physical and psychological levels provides us with the theoretical base for understanding how natural light interacts with architecture, and it is this knowledge that must be used to plan the functioning of light in buildings as a basic part of the project; it should never be postponed as a technique applicable to a previously defined project. Consequently, in our analysis we consider first and foremost the importance of light in fairly general design plans, relegating specific

Table 1
Light definers

Illuminance (general values)	
Activities with very high eye strain: precision drawing, jewellery etc.	1000 lux
Short-duration activities with high or very high eye strain: reading, drawing, etc.	750 lux
Short-duration activities with medium or high eye strain: work in general, meetings, etc.	500 lux
Short-duration activities with low or medium eye strain: storage, movement, social activities, etc.	250 lux

Table 2
Modifying factors for the general illuminance values

× 0.8	× 1	× 1.2
Age < 35 years Activity unimportant Low difficulty	Age 35–55 years Activity important Normal difficulty	Age 55 years Activity critical and unusual High difficulty

Table 3
Luminance values (with corresponding illuminances)

Visual code	Luminance (cd m ⁻²)	Horizontal illuminance (lux)
Human face hardly visible	1	20
Face fully visible	10–20	200
Optimum for normal work	100–400	2000
Surfaces with reflection > 0.2 well lit	> 1000	20,000

Table 4
Glare

Glare indices (<i>G</i>)	
Highly critical conditions with difficult work, dangerous situations, etc.	Imperceptible: < 13
Conditions with long-duration work of normal difficulty, with rest periods, etc.	Low: 13–16
Conditions with short-duration work or light work, with long breaks, etc.	Medium: 16–19
Conditions below critical, with short work periods, movement, etc.	High: 19–22
Conditions without visual requirements, in which glare is not a problem	Very high: > 22

Table 5
Colour of the light

Type of space	Condition	<i>R</i> (%)	<i>T_c</i> (K)
Spaces where colour is very important	Work	> 85	4500–6000
	Rest		2500–4000
Spaces where colour is important but not critical	Work	70–85	> 4000
	Rest		< 4000
Spaces where chromatic recognition is unimportant	Work	< 70	> 4500
	Rest		> 4500
Space without chromatic vision		40	Indifferent

Characteristics recommended according to use

systems and components of natural lighting to a secondary position, since they are often no more than forced solutions to problems that could have been solved more effectively at a previous stage in the project.

4.1. *Indoor and outdoor light*

Architecture is basically a contraposition of indoors and outdoors, sheltered space and exposed environment, confidence and vulnerability, privacy and society. During the day, natural light reveals the entirety of the exterior, filling all its corners and crudely showing the skin of buildings, their size, their shape and all their details (Fig. 14).

In these buildings, clearly visible in the intense natural light, openings are seen as dark holes that give few clues as to what is hidden indoors. In daylight hours, when light rationalizes the complex reality of our inhabitable environments, this same light renders the interior spaces of architecture invisible, private and mysterious. Even when the openings are covered with glass or whole façades of buildings attempt to reproduce the hard aesthetics of precious stones, being totally glazed, the interior of the architecture refuses to be observed during the day and the hard reflections of the glass defend the mystery of its interior.

In short, architecture is darkness during the day; only by penetrating its interior,

adapting our vision to indoor conditions (recall the slow adaptation when moving from light to dark), can we once again appreciate the architecture's interiors (Fig. 15).

On our wanderings around the interior spaces, the openings become powerful magnets, attracting our gaze towards the outside world, which seems more real and powerful than the dark interior in which we stand. As part and parcel of the attraction exerted by the view, we are dazzled by the high luminances of the exterior and no longer able to appreciate the details of the interior (Fig. 16).

For this reason, when light is used wisely in architecture it enters from outside the visual field of the observer, through high openings often located above the entry to the space. This restoration of an interior light of its own, from an unidentified source, exerts a rather magical effect. It renounces the external view in exchange for the reorganization of the interior space, which ceases to be secondary.

This whole situation changes radically at night, when the roles of the interior and the exterior are inverted. This is not the object of this work, although at this point two brief comments can be made on the use of artificial and natural light in architecture.

- (1) Both architecture and we who inhabit it are different by day and by night, therefore it makes no sense to try to imitate the effects of natural light with artificial light; the results will always be mediocre.
- (2) It is always difficult to combine the two kinds of light, due to their different chromatism and the fact that when the eye is accustomed to natural levels of light it finds artificial light poor and gloomy, whereas at night it seems ideal.

Returning to natural light as energy passing from the exterior to the interior of the building, it should be borne in mind that the way in which it enters is conditioned by its origin, which can be threefold (Fig. 17):

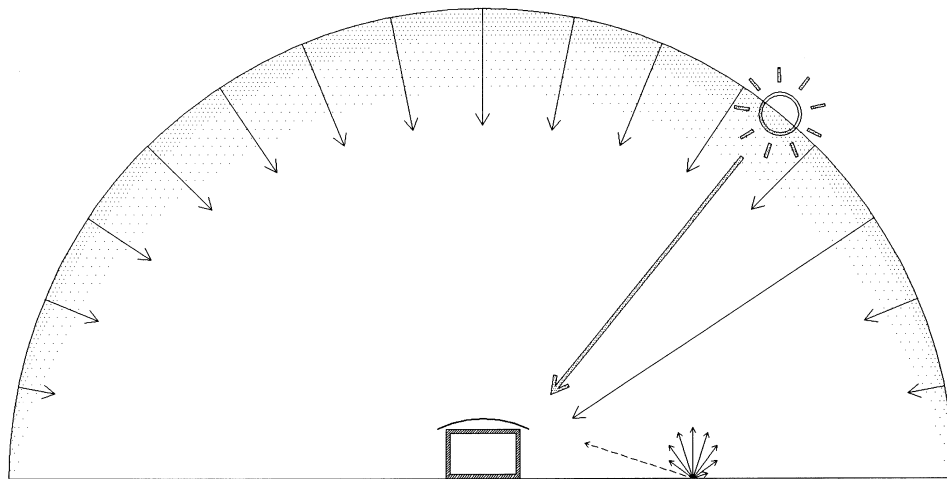


Fig. 17. Sky dome and building, showing three incidences: direct sun, sky dome and albedo.

- Direct sunlight is frequent in Mediterranean climates (see Section 6.1.), and strikes with parallel beams of high energy density (as high as $100,000 \text{ cd m}^{-2}$). Indoors it generates clearly defined patches of light that change as the sun moves across the sky dome. This type of light therefore creates uncomfortable interior visual conditions caused by excessive contrast, and easily results in overheating in interiors. Its thermal effect and its unique distribution of luminances, which imparts a feeling of cheerfulness, are desirable in winter and in cold climates and undesirable in summer in hot climates.
- Sky dome light is associated with an overcast sky (though it is also the case in clear skies for directions facing away from the sun), and is the most usual light in Atlantic and northern climates. Its lighting intensity is 10–20% weaker than direct sunlight and is also distributed in a more diffuse way, as it does not come from one single direction. This is the light which is often used as a minimum condition, but one must also consider that, in hotter climates, its entry into the building, even when direct radiation has been eliminated, can cause overheating problems.
- Reflected or albedo light from external surfaces becomes important when the other two types lack intensity, either because they are eradicated to avoid overheating or because the conditions of the premises or building do not allow direct access to skylight. In these circumstances, and when the external surfaces (the ground and neighbouring buildings) have relatively high reflectances, albedo light can generate useful interior lighting, although it should always be considered that since the light is not coming from above it has a greater tendency to cause glare.

Finally, bearing in mind the diffuse nature of both sky dome light and albedo light, in the absence of direct sunlight any opening behaves as if it were an emitting surface of diffuse light for the interior, since the luminances of the exterior can be considered to be transferred to the plane of the opening without any error of physics, the only correction necessary being the transmission coefficient of the glass, if present (Fig. 18).

4.2. *The perception of light in architecture*

When an architect imagines the architecture that he is beginning to design, he pictures in his brain the forms of the building he is creating, from overviews of the building to specific details of its façades. If he is sensitive to interior space, he will also imagine how the interior forms of its building will be when it is inhabited, thus becoming much more closely involved in the future architectural experience. Very few architects, however, are sensitive enough to imagine and design in their mind the light being planned for these spaces.

If we look at the works of the great masters of architecture, both ancient and modern, it is clear that in most cases natural light was present from the very first images of the projects they conceived. This conceptual presence of light is manifested not only in the results in the finished building, but can often be recognized as early as in the initial drawings that precede the actual result.

It is interesting to observe the different approaches architects have to natural light.



Fig. 14. Photograph of buildings from the exterior.

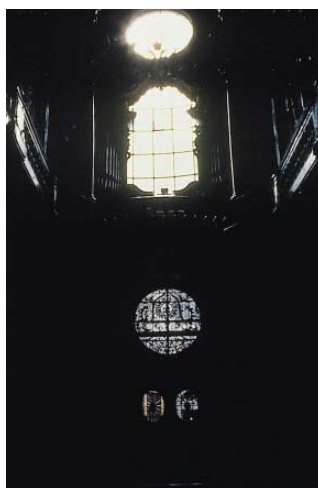


Fig. 15. Photograph of an interior, with dazzling windows.



Fig. 16. Photograph of an interior with 'hidden light', showing the light but not the opening.



Fig. 18. Photograph of entry of light through a window in two cases: direct sunlight/diffuse light.



Fig. 19. Photograph: light as a fluid.



Fig. 20. Photograph: light beams.



Fig. 21. Photograph: light as an impressionistic game.



Fig. 30. Photograph: intermediate lighting spaces.



Fig. 31. Photograph: interior light spaces.



Fig. 32. Photograph: lateral pass-through components.

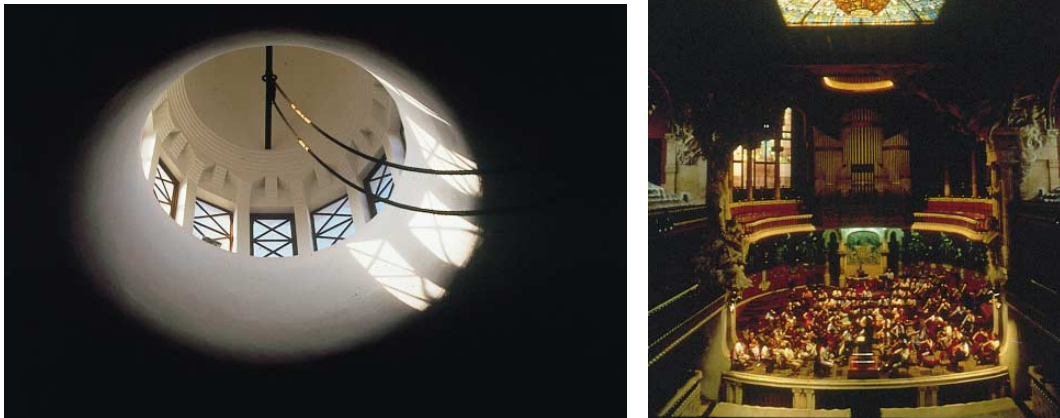


Fig. 33. Photograph:zenithal pass-through components.

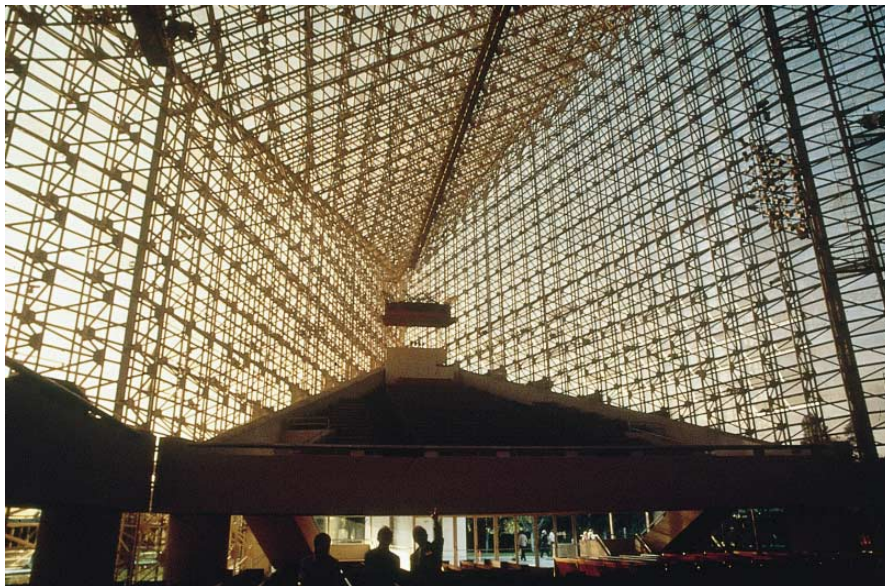


Fig. 34. Photograph: global pass-through components.



Fig. 35. Photograph: separator surfaces.



Fig. 36. Photograph: flexible screen.



Fig. 37. Photograph: rigid screens.



Fig. 38. Photograph: solar filters.



Fig. 39. Photograph: solar obstructors.

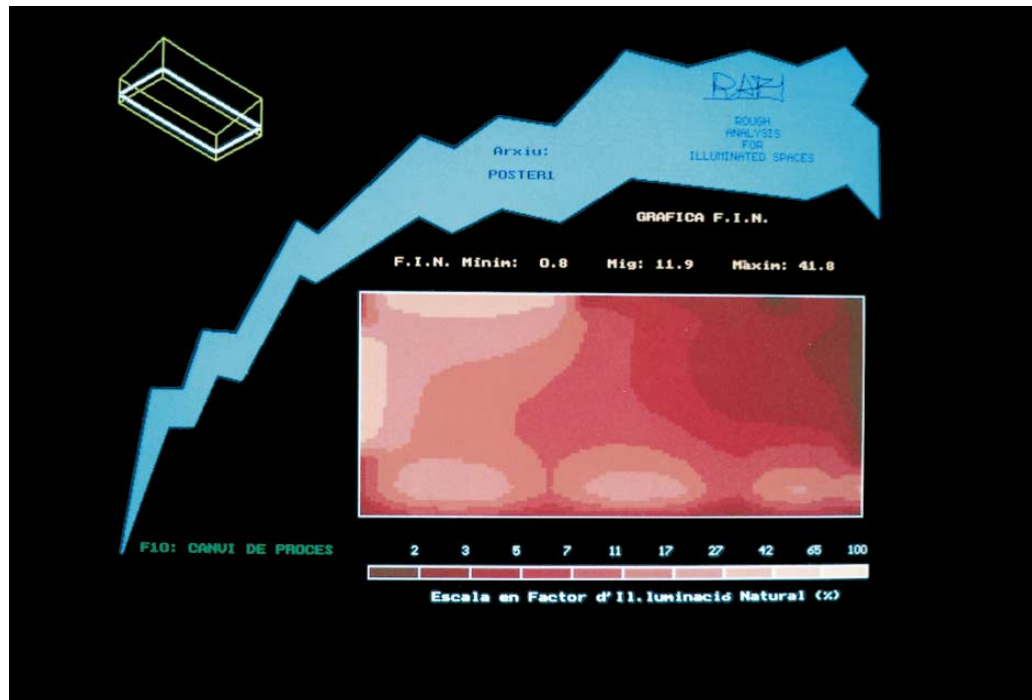


Fig. 40. Photograph: screen with isoDL graph.



Fig. 41. Photograph: scale model.

Quite apart from the greater or lesser knowledge they may have of the basic principles of lighting and even without assessing the efficiency of the results obtained, it appears that each one of them intuitively conceives the phenomenon of light differently, and this is reflected in the way in which light defines and shapes the spaces of their architecture (Fig. 19).

In many cases light is imagined as a fluid, liquid or gas that occupies all external space and spills or expands (according to how it is conceived), through the light openings and into the interior space. Faint patches of light define volumes, and transitions between spaces gives subtle meaning to the light that fills them. The lightness (i.e., luminance) of the surfaces are flat and undegraded, and only proximity to the openings reveals that the light fluid is entering with some lighter patches (Fig. 20).

In other cases light is understood as beams, in an almost mythological image of celestial force travelling through space, penetrating the interior and bouncing off surfaces, thus imbuing them with reality. Low-angle lighting therefore re-creates the material nature of construction elements and gradation shows the fatigue light suffers as it travels towards interior space (Fig. 21).

On other occasions natural light enacts an impressionistic game in an interior, independent patches of light only coming together to form a whole in the brain when the space is perceived globally. In such cases colour is decisive, and wall surfaces change the tone of the light they receive. Furthermore, shade takes on a value of its own, and the play of the absence of luminance can be more decisive than that of the actual light.

This analysis could unearth many other keys to the perception of light in architecture. Streams of light, silhouettes, rhythms of light and shade between spaces, the visible entry of light and the mystery of concealed entry, the magic of zenithal light, and so on. Whatever, it is clear that there is no such thing, nor should there be, as a single recipe or system for imagining light. The important thing is to nurture the will and the effort to imagine it; only in this way will architecture develop its full aesthetic potential.

4.3. *Lighting in peripheral and core zones*

The first point to tackle when considering the use of natural light is its entry into interiors that would otherwise be dark, due to the fact that they are separated from the exterior by a façade. Only the creation of openings in the shell of a building will allow the entry of natural light, in an inevitably limited yet controllable way.

In any building, two separate problems can be distinguished: the lighting of the peripheral zones or premises, which have contact with the skin of the building and therefore the possibility of direct access to the light outside; and that of the interior zones or premises, without contact with the shell, where the only access to natural light is by means of some system of transportation. These two problems, that of the peripheral zones and that of the core zones of the building, each have their own peculiarities, and they will be treated separately when considering possible solutions (Fig. 22).

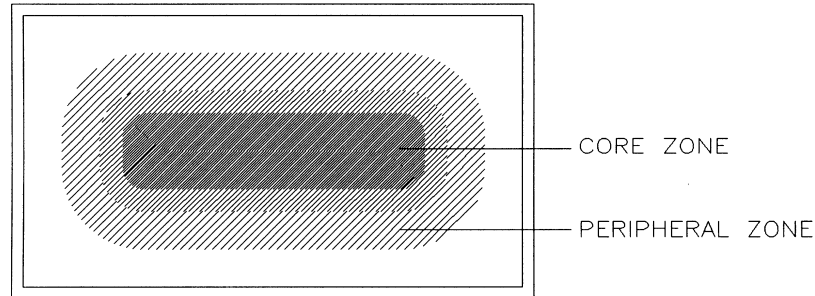


Fig. 22. Peripheral zone and core zone of a building.

However, before dealing with specific systems applying to the periphery or the core, we shall consider some general aspects of the project which affect its interrelation with light.

One initial point to consider is the compactness of the building, which establishes the relationship between the outer shell of the building and its volume, i.e., the degree of concentration of the interior spaces (Fig. 23).

Logically, less compact buildings will have greater possibilities of natural lighting, as the core zone, where the entry of light is more difficult to achieve, is correspondingly smaller.

Another aspect to be taken into account is the porosity of the building, which refers to the existence within its global volume of empty spaces and points of communication with the exterior, such as courtyards (Fig. 24).

A high degree of porosity indicates the possibility of creating an access for light (and also ventilation) in the core zones of the building. Although lighting by means of a courtyard will never be so effective as direct contact with the exterior, if the courtyard is suitably designed it can be very useful.

A further general aspect to consider is the transparency of the skin of the building to light, which varies from totally opaque buildings to totally glazed ones. Although greater transparency increases light in the peripheral zone, good lighting depends more on the appropriate distribution of light than on quantity. Often the effects of glare make lighting by means of large openings inadvisable.

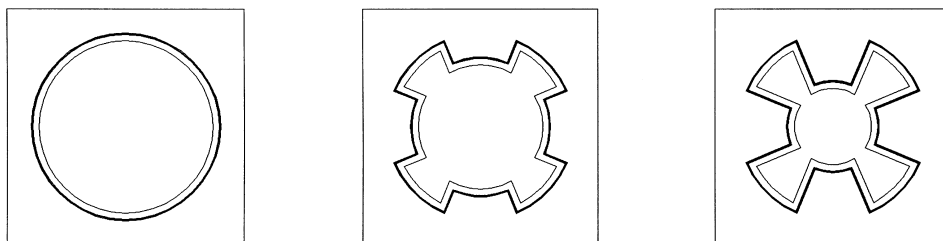


Fig. 23. Degrees of compactness of a building.

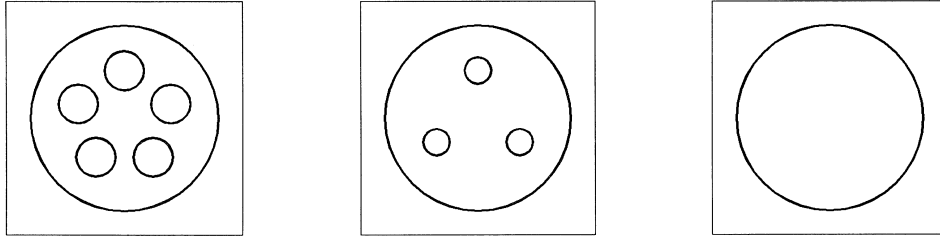


Fig. 24. Degrees of porosity of a building.

Other aspects to take into account are the geometric characteristics of the interior spaces. Premises can thus be analysed according to size, shape, proportions and possible differences in floor level.

The size of a building does not in principle have any influence on the distribution of light in its interior; areas of identical shape but different size and with their openings to scale with their size will have the same interior light distribution. Since radiant phenomena generally and light in particular do not change with size, the study scale of these phenomena can be accurately studied. The only point that should be borne in mind is that spaces with large surface area will have a dark central zone unless they preserve their proportions by having a higher ceiling (Fig. 25).

The shape and proportions of a building are important for its natural lighting, depending on the location of the opening. As a rule, irregular or elongated spaces with light entering at the end have a rather irregular light distribution (Fig. 26).

It should be taken into account that the lateral entry of light into a space causes a rapid decrease in light (i.e., illuminance) the further we are from the opening, due to the fact that the angle of vision of the sky (the main source of light) is soon lost. This results in peripheral zones and premises easily being badly lit, even if the total amount of light present is sufficient. The entry of zenithal light, on the other hand, tends to be more suitable (Fig. 27).

Finally, differences in the floor level have repercussions on both lighting and the view. If the floor drops towards the middle, the light distribution improves but the view is reduced, and vice versa (Fig. 28).

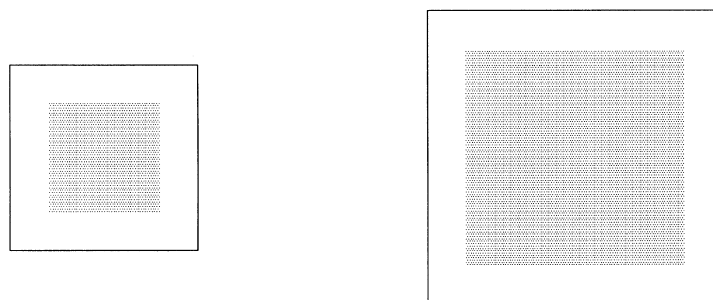


Fig. 25. Central zone in spaces with a large surface area.

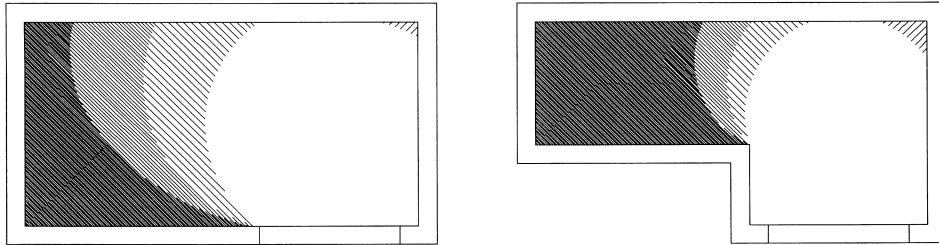


Fig. 26. Relationship between shape and light distribution.

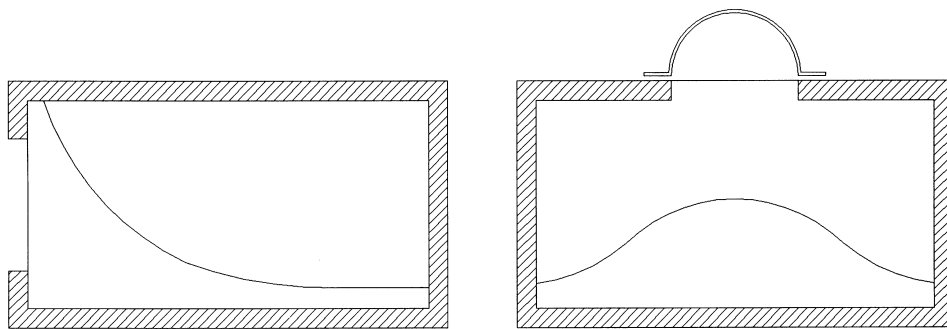


Fig. 27. Lighting levels with lateral and zenithal openings.

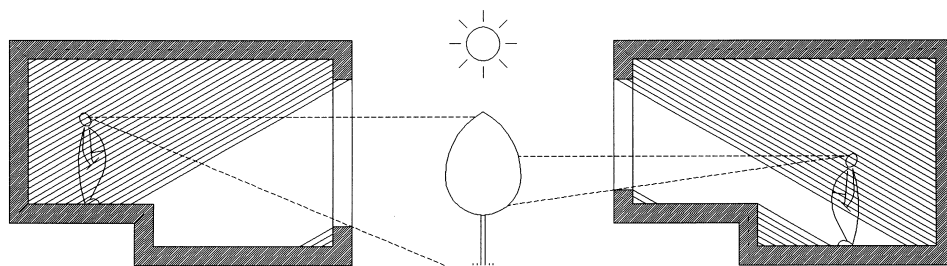


Fig. 28. Variation of light and views in stepped premises.

5. Daylighting improvement in buildings

Working from the basis of the considerations in the above sections, we shall now attempt to analyse natural lighting systems, considering them as a complementary strategy to the general lighting design of buildings.

Natural lighting systems are components or sets of components of a building the chief purpose of which is to improve the natural light of inhabitable spaces, optimizing the distribution of light in peripheral zones and attempting to bring as much natural light as possible into interior zones with no direct contact with the exterior. Among

the components of natural lighting we make a distinction between pass-through components and conduction components.

Conduction components are those which take natural light from the exterior towards interior zones of the building. They are frequently connected, forming continuous series.

Pass-through components are devices designed to allow the passage of light from a given light environment to one located next to it.

From this analysis, any combination or succession of pass-through and conduction components can be established, and we can interpret a building in lighting terms as a series of pass-through components placed between conduction components which connect them. In this way it is possible to schematize any complex system for the entry of natural light towards interior spaces (Fig. 29).

Pass-through components for natural light can be highly complex; so in order to analyse them we consider them as being composed of a set of control elements through which light passes. These control elements which make up the pass-through components correct the light reaching them and send it on to the neighbouring conduction component in a controlled way.

5.1. Conduction components to the core of the building

These are spaces that are located beyond an initial pass-through component which captures natural light from the exterior. They collect the light captured by the pass-through component, convey it to the next pass-through component and so on. Their shape is very important, since their capacity to conduct the light they receive depends to a large extent on the geometric characteristics of the conducting space.

The characteristics of the finish on their surfaces are also important, as this is where the natural light strikes. Different finishes cause components to act differently according to whether they are reflecting, specular, diffuse, absorbent or whatever.

Conduction components can be classed into two groups depending on their location in the building. They can be located between the external light environment or perimeter of the building and the interior spaces they are designed to illuminate, in

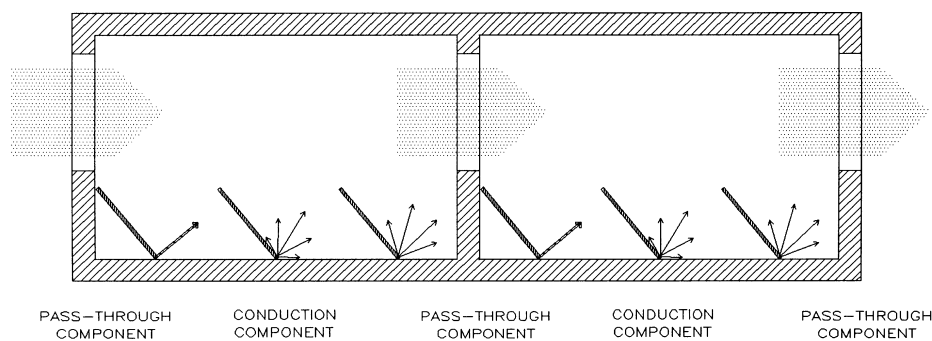


Fig. 29. Natural lighting components: conduction components and pass-through components.

which case we will call them intermediate light spaces. However, there are also conducting spaces that form part of the interior space of the building, relatively far from the periphery, and these we will call interior light spaces.

5.1.1. *Intermediate light spaces*

These are located in the peripheral zone of the building, between the external environment and the inhabitable spaces. They can act as regulatory filters between the internal and external environmental characteristics; they guide and distribute the natural light that reaches them from the exterior to the interior. They are sealed with transparent or translucent materials and can incorporate control elements to regulate light passing through. The most typical example are galleries, porches and greenhouses (Fig. 30).

They supply a low light level with little contrast with the interior, which they protect from the direct sun and the rain. Typically, they are one or two storeys high and 1–5 m deep.

5.1.2. *Interior light spaces*

These form part of the interior zone of a building, guiding the natural light that reaches them to interior inhabitable spaces that are far from the periphery. Within this group are courtyards, atria and all types of light-ducts and sun-ducts (Fig. 31).

They create light conditions that are intermediate between the interior and the exterior, and allow a degree of natural lighting in the interior zones of the building, which are connected by means of pass-through components.

Their size is very variable, although they are usually higher than they are wide. A light-coloured finish to their surfaces improves their performance, and a lining of mirrors converts them into sun-ducts.

5.2. *Peripheral components*

These are devices or sets of elements that connect two different light environments separated by a wall containing the component. They are defined by their geometric characteristics, namely, their size in relation to that of the wall in which they are set, their position in that wall (central or lateral, high or low) and the shape of the opening. Their composition depends on the elements they incorporate to control and regulate the lighting, visual and ventilation phenomena.

These components can be divided into three groups, according to the direction of incidence of the light in the inhabitable spaces. The three groups are: lateral pass-through components if the light enters the space to be lit on a vertical plane, zenithal pass-through components when the light tends to reach the interior from above and global pass-through components if the light comes into the interior space from both directions at once.

5.2.1. *Lateral pass-through components*

These are located in vertical enclosing surfaces, either in the skin of the building or in internal partition walls, between two environments with different lighting characteristics, and permit the lateral entry of light to the receiving area. Typical lateral

pass-through components are windows, balconies, translucent walls and curtain walls (Fig. 32).

They allow the lateral entry of light and direct solar radiation if they are in external façades, and often a view and natural ventilation. They greatly increase the light level near the window, but the distribution of light in the space is irregular.

Their dimensions are variable, from small windows measuring 0.1 m^2 to large glazed surfaces usually between 1.2 and 2.8 m high. They can be incorporated into all types of control elements.

5.2.2. *Zenithal pass-through components*

These are located in horizontal enclosing surfaces in the roof or the interior of a building, between two different light environments, and are designed to let zenithal light into the receiving environment below. Typical zenithal pass-through components in architecture are clerestories, monitor roofs, north-light roofs, translucent ceilings, skylights, domes and lanterns (Fig. 33).

They allow the entry of light from the sky dome and either protect or redirect the direct solar radiation towards the space below. They can also permit natural ventilation without an external view, and generate high lighting levels in the interior environment, usually with diffuse light, thus avoiding excessive contrasts.

The size of the openings is variable; they sometimes occupy a large proportion of the surface area of the ceiling over the space that it is intended to illuminate. They are seldom smaller than 2 m^2 .

5.2.3. *Global pass-through components*

These form part of the enclosing surfaces of a built structure, and are made of transparent or translucent material. They totally or partially surround the environment and permit the global entry of natural light.

The most typical component of this type is the membrane, with translucent or transparent surfaces, which surrounds the whole of an interior environment. It allows overall entry of light and generates a high, uniform light level in the interior, similar to external conditions (Fig. 34).

These components can easily cause problems of excess radiation in hot or moderate climates, especially in summer, when the sun's path is higher in the sky.

For this reason it is advisable to complement these components with radiation control elements to protect their whole surface. Furthermore, movable openings should be provided at their highest points to enable hot air to escape.

The surface area of these global components is usually greater than the ground plan of the space surrounded by the membrane. The materials commonly used for the enclosing surfaces are plastics (acrylic polycarbonates or glass fibres) supported by an aluminium or steel structure. In many cases, these pass-through components define the volume of peripheral conduction components such as greenhouses or atria.

5.3. *Control elements*

These devices are specially designed to enhance and/or control the entry of natural light through a pass-through component.

Among their general characteristics, we should consider their position in relation to the pass-through component that they are regulating, their mobility or possible regulation by the users of the spaces, and their optical properties, such as transparency, diffusion and the reflection of light.

In addition to their behaviour with regard to light, these control elements can serve other environmental purposes for the pass-through components, for instance, ventilation, the possibility of a controlled view, the thermal protection of the interior space or the safety of the building.

We shall classify the control elements in five general groups according to the way in which they control the incident light: separator surfaces between two different light spaces, screens in flexible materials, rigid screens or screens in rigid materials, selective filters for a particular characteristic of solar radiation and total radiation obstructors.

5.3.1. *Separator surfaces*

These are surface elements of transparent or translucent material, incorporated into a pass-through component that separates two different environments. They enable radiation, and sometimes the view of the exterior, to pass through, but block the passage of air. Among the numerous types of separator surface in existence in the field of architecture, there are conventional transparent ones, those with chemically or mechanically treated surfaces, those that follow a particular geometrical pattern and active enclosing surfaces (Fig. 35).

Conventional divisions are made of glass or transparent plastic. Treated divisions include all kinds of coloured glass, mirrored glass, translucent glass, and recently, glass incorporating thermochromic or holographic films. They are useful for the way they modify the characteristics of the light that passes through them, varying according to given geometric or thermal parameters. Geometric divisions are formed by sheets of a plastic material with optical properties due to its geometry, and redirect the incident light in a given direction. Finally, active divisions are manufactured with high-technology materials incorporated into their surface, and regulate the light that passes by means of electrical phenomena that modify the optical properties of the division.

5.3.2. *Flexible screens*

These are elements that partially or totally prevent the entry of solar radiation and make the light that shines through them diffuse. Depending how they are placed, they can allow ventilation and provide visual privacy. They can be retracted, rolled up or folded away to remove their influence when so wished. The commonest types of flexible screens are awnings and exterior curtains (Fig. 36).

Awnings and curtains are made of materials that are either opaque or serve to diffuse light. They can be placed over the external surface of a pass-through component, so as to selectively prevent radiation passing prior to entry or, by placing them over the interior of separator surfaces, control the radiation that has already entered the pass-through component and is illuminating the interior.

5.3.3. *Rigid screens*

These are opaque elements that redirect and/or block the direct solar radiation that strikes a pass-through component. Normally, they are fixed and unadjustable, though there may be exceptions to this. Their main variable is their position with relation to the opening they protect. Among the various possible types we shall put special emphasis on overhangs, light-shelves, sills, fins and baffles (Fig. 37).

Screens can be specifically placed in any position, where they are intended to block or reflect the sun's rays coming from particular directions.

5.3.4. *Solar filters*

These are surface elements that cover all, or nearly all, of the outer face of a pass-through component, protect it from solar radiation and allow ventilation. They can be fixed or movable (so that they can be removed and the opening left free), and adjustable if the orientation of the louvres of which they consist can be changed. Those most used in architecture are the various types of blinds and jalousies (Fig. 38).

They are very widely used in architecture, in many different climates and cultures. This explains the great variety of possible forms and materials available for this extremely popular mechanism.

5.3.5. *Solar obstructors*

These are surface elements composed of opaque materials, and can be attached to the opening of a pass-through component in order to completely seal it. They are normally called shutters and can be located either on the exterior or on the interior of a glass separator surface (Fig. 39).

The effect they have on the entry of light into inhabitable interior spaces is heightened by their effect on visual control and thermal insulation. They act as barriers to all effects, at times when users wish to neutralize interactions between the external environment and the interior through the pass-through components which they modify.

6. Conditions of the sky

6.1. *The luminance of the sky*

The luminance of the sky is a basic characteristic to be taken into consideration when studying the pre-existing conditions of a site, and the local climate, with its associated degree of cloud cover, is a decisive factor in this.

There are several different possible models for the luminance of the sky to take into account as a pre-existing environmental condition in a given place. As a rule, an overcast sky is taken to be the most unfavourable case, and this alone is studied. This is logical in northern climates, but not in temperate ones, where the cases of cloudy and clear skies should also be considered, as should the position of the unobstructed sun, protection from it and the exploitation of its radiation both requiring attention.

Table 6

The values for the mean luminance of the sky dome for latitude 40°, with different climatic conditions and times of year

Winter solstice			Equinoxes			Summer solstice		
08:00	10:00	12:00	08:00	10:00	12:00	08:00	1:00	12:00
16:00	14:00			16:00	14:00		16:00	14:00
1750	3200	4700	3200	4600	6200	6000	7600	8600
4600	21,000	24,000	22,000	28,000	30,000	27,000	31,000	32,000

The values in the first row correspond to mean luminance with an overcast sky, while the second row is for a clear sky. The minimal case at Mediterranean latitudes is taken to be an overcast sky with 3200 cd m⁻², which is equivalent to some 10,000 lux on a horizontal plane without obstructions.

It should be borne in mind that Mediterranean climates have direct sunlight much more frequently (70% of the time) than more northern climates (30% of the time); this is often neglected when studying the natural lighting of buildings.

6.1.1. Uniform overcast sky

This is the main model used in natural lighting studies, with constant luminance in all directions and heights. The relationship between the mean luminance of the sky and the illuminance of a horizontal plane without any obstruction will be:

$$E_h = \pi L \quad (7)$$

where:

E_h = illuminance on horizontal plane (lux)

L = mean illuminance of the sky (cd m⁻²)

The values for the mean luminance of the sky dome for latitude 40°, with different climatic conditions and times of year are in Table 6.

6.1.2. CIE overcast sky

This is the model for the standard overcast sky, which provides a better fit with reality, since luminance varies with height, to the extent that the sky is considered to be three times lighter at the zenith than at the horizon.

This relationship is defined with the Moon–Spencer formula:

$$L_\alpha = L_z \left(\frac{1 + 2 \sin \alpha}{3} \right) \quad (8)$$

where:

L_α = luminance at a height with angle α above the horizon

L_z = luminance at the zenith

In this case L_z can be considered to be 9/7 of the (uniform) mean luminance of the sky.

Another correcting factor to be taken into account in this analysis is the variation of the luminance of the sky depending on direction, not only with a cloudy or clear sky but also with an overcast one.

This variation in the luminance can be expressed, for luminance at the horizon, as a 20% increase in the direction of the equator and likewise a 20% decrease in the direction of the pole of the hemisphere concerned. These variations diminish with increasing height, finally disappearing at the zenith.

The Moon–Spencer expression, duly corrected to allow for this variation, would be:

$$L_{\alpha,\beta} = L_z \left(\frac{1 + 2 \sin \alpha}{3} \right) (1 + 0.2 \cos \beta) \quad (9)$$

where:

$L_{\alpha,\beta}$ = luminance of the sky for a height β in the direction of the equator
 L_z = luminance at the zenith

6.1.3. Clear sky

For the case of a clear sky the best strategy is to consider only the direct incidence of the sun, with an intensity in the order of 100,000 cd m⁻² and the position corresponding to the time of the year and day.

We will also consider, as indirect sources, the rest of the sky dome and reflection from other surfaces on the ground or other external elements (albedo).

For the case of a clear sky dome, luminance decreases as we move away from the sun, with values varying between 2000 and 9000 cd m⁻².

For the case of the albedo, the typical luminance value is taken as the result of applying the following expression:

$$L_a = E_h r / \pi \quad (10)$$

where:

L_a = luminance of albedo
 E_h = illuminance received by the surfaces (estimated at 100,000 lux for a clear sky)
 r = reflection coefficient of the surfaces (typical value of 0.2, or as high as 0.7 on light surfaces)

6.1.4. Cloudy sky

In the case of a cloudy sky, intermediate between a clear and an overcast sky, hypotheses must be made which correspond to a situation somewhere between those considered in the above cases. Nevertheless, if the two extremes are known, it is not necessary to study this type of sky beyond ascertaining its frequency for each time of year.

6.2. Compilation of data

Compiling data on this topic is difficult, but often meteorological services give percentages of clear, cloudy and overcast days for each month of the year, and this information can be used as a good approximation of the conditions of the sky that can be expected in a given place.

7. Daylighting evaluation in architecture

The aim of a natural lighting dimensioning method for a project or building is to ascertain the amount of light in the interior environment, together with its distribution.

In natural lighting there is so much variability in the factors that generate the environment that evaluation systems are inexact. Calculations provide us with knowledge of interior conditions in relation to exterior ones which we know to be changing. Because of this, results are expressed as percentages of the exterior level, and are called daylighting factors (*DL*):

$$DL = 100 \times E_i(\text{interior})/E_e(\text{exterior}) \quad (11)$$

Generally speaking, natural light calculation systems fall into one of the following categories: predimensioning methods, point-by-point methods and computer-assisted exact calculation. There are also evaluation systems that use scale models.

The first of these shows approximately how much light will enter the space and from this enables us to deduce the resulting mean illuminance on a working plane. The problem with this method is that, since the distribution of light in an interior tends to be irregular, the mean value reached gives little information about the resulting light environment. Only in the cases of diffusive zenithal systems or comparative general evaluations can this system be considered useful.

Point-by-point systems give the light distribution within the premises by means of the repetitive calculation of the light arriving from the openings at each point in a theoretical network or mesh covering the working plane in question. This system provides a better evaluation of the resulting environment and can be used to produce graphs of relative illuminance value, but its precision is low, since it fails to consider the effect of light reflection on the interior walls.

Computer systems not only permit point-by-point calculation but also take interior reflection into account. The results they yield are highly accurate, their only weak point being the lack of reliability of data on outdoor light, which can only be improved with detailed statistics on the average conditions of the sky.

The resulting system for the representation of light is very important. It can be derived from any method that gives point-by-point values. Using the mesh of points which represents the premises, 'isolux' or 'isoDL' curves can be drawn joining points of equal illuminance value, for fixed values every 50 or 100 lx, or every 2, 5 or 10 *DL*. These curves, similar to those drawn on a topographic map, provide very good visual information on the distribution of light in the space (Fig. 40).

7.1. Predimensioning method

The most commonly used lighting predimensioning method, both for its simplicity and the relative accuracy of the values it gives considering the time needed to make the calculations, is the flux method.

The result given is the mean illuminance on a working plane situated just above the floor in an interior space. The formulation is as follows:

$$E_i = \frac{E_e S_{\text{pas}} v t u}{S_i} \quad (12)$$

where:

E_i = interior illuminance, in lux

E_e = mean exterior illuminance on a horizontal plane, in lux

(Normal figures in the calculations are 10,000 lx per overcast day in winter and 100,000 lx per clear day in summer.)

S_{pas} = total surface area of openings for light to pass through, in m²

v = opening factor, or solid angle of sky seen from the opening as a proportion of the total solid angle of the sky (2π), over 1 (on a vertical plane, 0.5)

t = transmission factor of the enclosing surface as a whole, over 1 (normally under 0.7)

u = utilization coefficient, or ratio between the flux reaching the lit plane and the flux entering the premises through the opening, over 1 (value of 0.2–0.65)

S_i = surface area of the premises, in m²

7.2. Point-by-point calculation method

This method calculates the resulting illuminance for each of the points chosen, which together form a metre-square mesh, and for each of the openings, considered as diffuse emitting surfaces. The basic formulae applied are:

$$E = \frac{I \cos \alpha}{d^2} \quad (13)$$

where:

E = resulting illuminance, in lux

I = intensity reaching the point, in candelas

α = angle at which the light arrives from the opening

d = distance from the centre of the opening to the point, in m

$$I = L S_o \quad (14)$$

where:

L = illuminance of the opening, in cd m⁻²

S_o = surface area of the opening, in m²

$$L = \frac{E_o}{\pi} \quad (15)$$

where:

E_o = illuminance emerging from the opening

$$E_o = E_e v t \quad (16)$$

where:

E_e = mean exterior illuminance on a horizontal plane, in lux

v = opening factor, or solid angle of sky seen from the opening as a proportion of the total solid angle of the sky (2π), over 1

t = global transmission factor of the enclosing surface, over 1

There exist tables and graphic abaci that can be used to calculate the opening factor v and the mean exterior illuminance on a horizontal plane E_e , depending on the geometric situation of the openings in relation to the exterior and the lit point.

7.3. Computer calculation methods

These make use of the powers of computer calculation to integrate the results of the light reaching each point from openings and interior reflections alike. In fact they apply the point-by-point system with all the necessary iterations to obtain great accuracy.

7.3.1. Evaluation methods using scale models

The use of scale models in architecture to evaluate natural lighting has a long tradition. Physical models reproduce in miniature the building that it is intended to build, their strength residing in the fact, mentioned above, that radiant phenomena are stable despite scale changes in space, basically as a result of the short wavelength of light in comparison with the size of spaces.

Model buildings must mimic the exact form and the finish of surfaces, including colours. Likewise, the openings for the entry of light should reproduce those in reality, with materials for the enclosing surfaces that behave identically to those planned for the building.

Scale models make it possible to evaluate complex configurations and shapes which are difficult to reproduce in computer models, and have the further advantage that the resulting light in the space being designed can be visualized easily. The behaviour of the building with regard to light can be tested in different ways:

The simplest process is to use the real sky, but this depends on climatic conditions, and a great number of experiments are needed to evaluate the results for different times of year.

With artificial skies, the procedure is costlier, but the fact of working in a laboratory allows greater input control. Various types of devices can be used with these methods;

mirror chambers can easily render overcast sky conditions, shading tables make it possible to study the effects of direct sunlight cheaply, and finally, the more expensive hemispheric sky simulator can make a global reproduction of the natural sky in any circumstance (Fig. 41).

Nevertheless, it should be borne in mind that evaluation systems, whether they be manual, computer-assisted or using scale models, are no substitute for a sound approach to the project, and this depends above all on the attitude of the designer, which should be based on a good understanding of the physical and physiological principles of light and vision.